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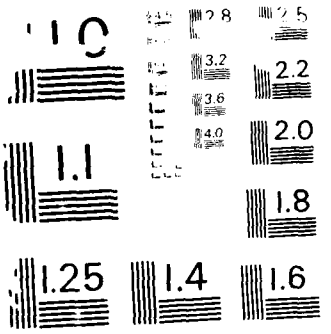

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Summary

The progress achieved over the four years of the Saguaro distributed operating system project is presented. The major accomplishments include design of the full system, prototype implementations of major system components on top of UNIX, and the implementation of portions of the system using the distributed programming language SR. Substantial work was also performed on related research, including SR, the MLP system for constructing distributed mixed-language programs, the Psync interprocess communication mechanism, the *x* configurable operating system kernel, and the development of language mechanisms for performing failure handling in distributed programming languages.

Research Accomplishments

Over the past four years, we have made significant progress on the design and implementation of the Saguaro distributed operating system. Substantial work has also been performed on related research, including the SR distributed programming language, the MLP system for constructing distributed mixed-language programs, the Psync interprocess communication mechanism, the *x* configurable operating system kernel, and the design of language mechanisms for handling failures in distributed programs.

Saguaro is a new operating system for computers connected by a local-area network. Systems constructed on such an architecture have the potential advantages of concurrency and robustness. In Saguaro, these advantages are made available to the user through several mechanisms. One is *channels*, a facility that allows the input and output of different user commands to be connected to form general graphs of communicating processes. Two additional mechanisms are provided to support semi-transparent file replication and access: *reproduction sets* and *metafiles*. The advantages of concurrency and robustness are also realized at the system level by the use of pools of server processes and decentralized allocation protocols. Finally, Saguaro makes extensive use of the *Universal Type System* (UTS), a data description language to describe user data such as files and to specify the types of arguments to commands and procedures. This enables the system to assist in type checking and leads to a user interface in which command-specific templates are available to facilitate command invocation.

A number of papers have been written describing various aspects of Saguaro. An early description of the system is reported in [1], while a subsequent paper describing the design of the system appears in [2]. Another paper describing the mechanisms for enhancing file availability appears in [3]. A related paper describes the implementation and use of reproduction sets and metafiles in a UNIX environment [4]. The entire file system has now been implemented on Sun workstations; this work is described in detail in a Ph.D. dissertation [5]. Summaries of Saguaro and the related projects also appear in the proceedings of two workshops on experimental distributed systems [6]. Finally, a formal derivation of a rectangle partitioning algorithm motivated by the window manipulation necessary for the Saguaro user interface is outlined in [7].

As mentioned, significant progress has also been made on related projects. One of these is further development of the SR distributed programming language, which has been used to implement the Saguaro file system and will be used to implement the rest of Saguaro. Over the past several years, a large amount of effort was expended revising SR and implementing a compiler for the new version. The main language constructs are still resources and operations: resources encapsulate processes and variables they share, operations provide the primary mechanism for process interaction. One way in which SR has changed is that both resources and processes are now created dynamically. Another change is that the mechanisms for operation invocation—**call** and **send**—and operation implementation—**proc** and **in**—have been extended and integrated. Consequently, all of local and remote procedure call, rendezvous, dynamic process creation, asynchronous message passing, multicast, and semaphores are supported. We have found this flexibility to be very useful for distributed programming. The language has also been refined in numerous additional ways to provide additional flexibility. Moreover, by basing

SR on a small number of well-integrated concepts, the language is also relatively simple and has a reasonably efficient implementation.

The compiler and runtime support currently execute on top of UNIX; they have been in use since November 1985. Since that time, numerous small enhancements to the language have been made, mainly in response to comments from users. SR now runs on both Vaxes and Suns and most of the language features have been implemented. The implementation is currently in beta test and will soon be ready for release to whomever is interested.

The current version of the SR language is defined in [8]. An overview of the language and its implementation is given in [9], while an earlier version of the language is documented in two technical reports [10, 11]. A detailed discussion of how SR has evolved—what has changed and why as well as what has not changed and why not—is given in [12]. Much of this work was performed as part of the dissertation research of a recently completed doctoral student [13]. Experience using the language to implement the Saguaro file system appears in [5]. In addition, the variety of communication primitives provided by SR has facilitated the research of Stella Atkins, who was a visiting professor at Arizona during Spring 1986 [14, 15].

A second Saguaro-related project is the MLP system for constructing distributed, mixed language programs. This system allows users to write sequential programs in which each procedure can be written in any one of several programming languages and located on any machine in a network. In effect, MLP allows heterogeneity in language and machine functionality to be exploited by the addition of a general remote procedure call facility to each supported language. Writing an MLP program involves three steps: the addition of interface specifications written in UTS to each procedure, translation of the augmented source using an MLP translator for the given host language, and the invocation of the MLP linker to produce an executable program. At run-time, values are transmitted between procedures using a machine and language independent data representation; conversions between such values and their equivalent host language values are performed automatically in most cases. The system executes on a collection of Vaxes and Suns running Berkeley UNIX. Currently supported languages are C, Pascal, and Icon. Work has recently begun on a second version of the system.

The UTS system and its application to mixed language programming are described in [16]. A description of the implementation of MLP and our experience in using the system appears in [17]. A user's manual on the MLP system has also been written [18], as has a report describing how to add a new language to the system [19]. The way in which the object-oriented distributed programming language Emerald is being integrated into the second version of the system appears in [20].

Another line of research has involved two separate projects investigating aspects of interprocess communication. The first is Psync, an interprocess communication mechanism that supports a new abstraction through which a group of processes can exchange messages. The novel aspect of Psync is that it preserves the *happened before* partial ordering of messages exchanged among multiple processes. Just as physical clock signals are encoded with data bits in a raw communication channel to help keep the source and destination synchronized, Psync explicitly embeds timing information drawn from the distributed computation's *logical clock*.

We have recently implemented and experimented with a prototype version of Psync. The prototype demonstrates that recording the happened before relation in the communications subsystem can be implemented on an unreliable communications network at little cost. Also, the abstraction provided by Psync is general enough to support efficient and elegant implementations of a wide spectrum of communication paradigms.

The second project is the *x*-kernel, a configurable operating system kernel designed to support experimentation in interprocess communication and distributed programming. The *x*-kernel's underlying architecture provides a rich set of abstractions that are used to construct and compose communication protocols. The architecture is interesting because the these abstractions are both general enough to accommodate a wide range of protocols and efficient enough to provide a useful testbed in which protocol performance can be accurately measured.

An initial description of Psync appears in [21] (that paper was selected as the outstanding paper at its symposium). A more comprehensive paper that includes discussion of the implementation is currently nearing completion [22]. The design of the *x*-kernel is documented in [23].

The final related line of investigation has been developing language mechanisms for handling failures. One property that makes failures difficult to handle in distributed systems is that they can occur concurrently with other system events. We have been investigating an approach for writing fault-tolerant distributed programs that can cope with such asynchrony in a systematic manner. The basic idea is to treat failures as just another class of events that are handled similarly to normal system events. Linguistic constructs that can be added to distributed programming languages with minimal impact are then proposed to handle such failure events. Although our approach is applicable to most concurrent languages, to make our ideas precise we have been using the SR distributed programming language as a basis for incorporating these constructs. Two non-trivial fault-tolerant protocols have been written in this extended SR language: replicated directory management and two-phase commit. The class of failures considered are those suffered by fail-stop processors.

Our initial proposal for failure handling mechanisms is described in [24]. The mechanisms have recently been refined and extended, as described in [25].

Finally, a paper has been written that surveys several of these projects in distributed languages and systems, and offers observations based on the experience gained during their design, implementation, and use [26]. The relevant projects are the SR distributed programming language, the Saguaro distributed operating system, the MLP system for constructing distributed mixed-language programs, the object-based distributed programming language Emerald, and the Psync interprocess communication mechanism. The observations address the experimentation process itself as well as the design of distributed software.

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